SHELL HYDROGEN STUDY
ENERGY OF THE FUTURE?
Sustainable Mobility through Fuel Cells and H₂

In cooperation with Wuppertal Institut
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SHELL HYDROGEN STUDY

- Shell scenario studies (since 1958)
- Shell → H₂ R&D, production and use
- Own business Unit Shell Hydrogen
- Shell hydrogen study → objectives:
  - Future potentials of hydrogen
  - Analyse business opportunities
  - Focus on (auto)mobility applications
  - Inform business partners, customers, stakeholders
- Collaboration with think-tank Wuppertal Institut
CONTENTS

1) Properties of H₂
2) Production and supply pathways
3) Storage and transport
4) Applications → material or energy
5) Stationary applications
6) Mobility applications (TR Levels)
7) Ownership cost of FCEVs
8) Retail infrastructure build-up
9) FCEV fleets, energy and greenhouse gas balances
THE ELEMENT HYDROGEN

Water will be the coal of the future.

Jules Verne
„The Mysterious Island“
1874

Jules Verne: water – the new coal?

Dieter Zetsche: hydrogen – the better oil?

Which future role for hydrogen as an energy carrier?
PHASE DIAGRAM HYDROGEN

- Solid
- Liquid
- Gaseous
- Supercritical fluid
- Critical point 13 bar, -240°

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IGNITION RANGES OF FUELS

- Hydrogen
- Methane
- Propane
- Ethanol
- Petrol
- Biodiesel
- Diesel

Legend:
- Mixture too lean
- Ignition range
- Mixture too rich

Gestis 2017, own diagram
SHARE OF PRIMARY ENERGY CARRIERS IN GLOBAL HYDROGEN PRODUCTION

- Gas: 68%
- Oil: 16%
- Coal: 11%
- Electricity: 5%

E4tech 2014; own diagram
PROCESSES FOR PRODUCING HYDROGEN

**PRIMARY ENERGY**
- Solar, Wind
- Algae from sunlight
- Biomass
- Natural Gas
- Oil
- Coal

**SECONDARY ENERGY**
- Electricity
- Biomethane
- Biogas
- Ethanol
- Vegetable Oils

**CONVERSION**
- ELECTROLYSIS
- BIOCHEMICAL CONVERSION
- THERMOCHEMICAL CONVERSION
  - SMR: Steam methane reforming
  - POX: Partial oxidation
  - ATR: Autothermal reforming

**INTERMEDIARY PRODUCT**
- Syngas

**FINAL ENERGY CARRIER**
- HYDROGEN
THE PRINCIPLE OF AN ALKALINE ELECTROLYSER

\[ \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2 \text{O} + \frac{1}{2} \text{O}_2 + 2e^- \]

\[ 2 \text{OH}^- + 2e^- \rightarrow \text{H}_2 + 2 \text{OH}^- \]
SECTOR COUPLING: POWER-TO-X PATHWAYS

POWER-TO-GAS

CO₂ → Methanation → Methane PtCH₄

POWER-TO-LIQUIDS

CO₂ → Storage caverns → Synthesis → Petrol, Diesel, Jet fuel
ENERGY INPUT FOR HYDROGEN SUPPLY

4.5 MJ/MJ $H_2$

3.5

2.5

1.5

0.5

- EU Gas-Mix Reforming
- Biogas-Mix Reforming
- LNG Reforming
- EU Electricity-Mix Electrolysis
- Renewable Electricity Electrolysis

JEC 2014; own diagram

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GREENHOUSE GAS EMISSIONS OF HYDROGEN SUPPLY

250 g CO₂/MJ H₂

- Centralised Paths
- Decentralised Paths

EU Gas-Mix Reforming
Biogas-Mix Reforming
LNG Reforming
EU Electricity-Mix Electrolysis
Renewable Electricity Electrolysis

JEC 2014; own diagram
HYDROGEN PRODUCTION COSTS

12 €/kg H₂

LBST/Hinico 2015; Grube/Höhlein 2013, own diagram

Current    Projected    Min. - Max.

Centralised Gas Reforming  Decentralised Gas Reforming  Centralised Electrolysis  Decentralised Electrolysis  Centralised Biomass  Decentralised Biomass
# HYDROGEN STORAGE METHODS

## PHYSICAL

<table>
<thead>
<tr>
<th>Method</th>
<th>Pressure (bar)</th>
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<tbody>
<tr>
<td>Compressed Gaseous Hydrogen</td>
<td>CGH₂ (350, 700)</td>
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<tr>
<td>Cryo-compressed Hydrogen</td>
<td>CcH₂</td>
</tr>
<tr>
<td>Liquefied Hydrogen</td>
<td>LH₂</td>
</tr>
<tr>
<td>Slush Hydrogen</td>
<td>SH₂</td>
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</table>

## MATERIALS-BASED

<table>
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<tr>
<th>Type</th>
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<tbody>
<tr>
<td>Metal Hydrides</td>
<td></td>
</tr>
<tr>
<td>Liquid Organic Hydrogen Carriers</td>
<td>LOHCs</td>
</tr>
<tr>
<td>Sorbents (MOFs, Zeolites, Nanotubes)</td>
<td></td>
</tr>
</tbody>
</table>
HYDROGEN STORAGE DENSITY

- LH₂ (80 g/l, 1 bar, -253°C)
- CcH₂ (60 g/l, 300 bar, -235°C)
- SH₂ (40 g/l, 1 bar, -259°C)
- CGH₂ (20 g/l, 350 bar, 15°C, 700 bar, 15°C, 1 bar, -253°C)

BMW 2012; Eichhölder/Klell 2012; own diagram

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STORAGE DENSITY OF TANK SYSTEMS

35 MJ/kg
30
25
20
15
10
5
0

Petrol
FCEV
BEV

IEC 2013 VDE 2015; own calculation
HYDROGEN ROAD TRANSPORT

TUBE TRAILER
200 – 250 bar, ≈ 500 kg, ambient temperature

CONTAINER TRAILER
500 bar, ≈ 1,000 kg, ambient temperature

LIQUID TRAILER
1 – 4 bar, ≈ 4,000 kg, cryogenic temperature
HYDROGEN PIPELINES PER COUNTRY

- USA 2,608 km
- Belgium 613 km
- Germany 376 km
- France 303 km
- Netherlands 237 km
- Canada 147 km
- Others 258 km

HyARC 2017; own diagram
GLOBAL USAGE OF HYDROGEN

- Ammonia: 55%
- Methanol: 10%
- Refining: 25%
- Other: 10%

Zakkour/Cook 2010; own diagram
PRINCIPLE OF THE FUEL CELL

$\text{H}_2 + \frac{1}{2} \text{O}_2 = \text{H}_2\text{O}$

HEAT
STATIONARY APPLICATIONS

Backup Power

Electrical efficiency up to 45%

System efficiency up to 95%
OWNERSHIP COST OF DOMESTIC ENERGY

Assumptions of TCO calculation:
- Reference building 150 m² living space
- Heat: low-temperature gas boiler with consumption of 22,500 kWh/a,
- Electricity consumption 4,000 kWh/a
- Installation + energy cost, 20 years lifetime

Three modernisation options:
- Condensing gas boiler (€ 7,000)
- Air sourced heat pump (€ 12,000)
- Micro-CHP fuel cell (€ 20,000)
TECHNOLOGY READINESS LEVELS OF HYDROGEN APPLICATIONS

TRL
9
9
Space Travel
9
Industrial Trucks
9
Stationary Applications
9
Passenger Cars
8
7
7
Buses
7
Light Rail
8
6-7
6-7
Shunting Locos
6-7
Motorcycle
6-7
Lorries
6-5
6-5
Aviation
6-5
Shipping
5
5

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FUEL CELL CONCEPTS FOR PASSENGER CARS

BEV WITH RANGE EXTENDER

Battery — Converter — Electric motor — Battery
Fuel cell — Hydrogen tank

FUEL CELL-DOMINANT SYSTEM

Battery — Converter — Electric motor — Battery
Hydrogen tank — Fuel cell — Electric motor
FUEL COSTS COMPARED*

* European fuel prices, passenger cars 2020+ (JEC 2014)
OWNERSHIP COSTS: FCEV AND PETROL VEHICLES

- **FCEV 2010+** 9.50 €/kg H₂
- **Petrol Hybrid 2020+** 2.50 €/l
- **Petrol 2020+** 1.50 €/l
- **FCEV 2020+** 7 €/kg H₂

![Graph showing ownership costs for FCEV and petrol vehicles over total mileage in km.]
OWNERSHIP COSTS: FCEV AND BEV

FCEV 2010+ 9.50 €/kg H₂
FCEV 2020+ 7 €/kg H₂
BEV 2020+ 35 ct/kWh
BEV 2020+ 20 ct/kWh

Total mileage in km
COMPONENTS OF A HYDROGEN REFUELLING STATION

**UPSTREAM**

1. **Electrolyser**

**REFUELLING STATION**

2. **Low-Pressure Storage**

3. **Compressor**

4. **High-Pressure Storage**

5. **Precooling**

6. **Dispenser**
SUPPLY PATHWAYS:
DECENTRALISED HYDROGEN PRODUCTION ON A RETAIL SITE
# Classes of Hydrogen Refuelling Stations by Size

<table>
<thead>
<tr>
<th></th>
<th>Very small XS</th>
<th>Small S</th>
<th>Medium M</th>
<th>Large L</th>
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<tbody>
<tr>
<td>Dispenser</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Max throughput per day</td>
<td>80 kg</td>
<td>212 kg</td>
<td>420 kg</td>
<td>1,000 kg</td>
</tr>
<tr>
<td>Max no. of refuellings per day</td>
<td>20</td>
<td>38</td>
<td>75</td>
<td>180</td>
</tr>
<tr>
<td>Max no. of FCEVs supplied per station</td>
<td>100</td>
<td>400</td>
<td>800</td>
<td>1600</td>
</tr>
</tbody>
</table>
SPECIFIC WELL-TO-WHEEL PASSENGER CAR GREENHOUSE GAS EMISSIONS “REAL WORLD” DRIVING CONDITIONS, EUROPE

200 g CO₂/ km

<table>
<thead>
<tr>
<th>Year</th>
<th>Tank-to-Wheel</th>
<th>Well-to-Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>160</td>
<td>40</td>
</tr>
<tr>
<td>2030</td>
<td>120</td>
<td>40</td>
</tr>
<tr>
<td>2040</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>2050</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

**PETROL**
- E10

**PETROL HYBRID**
- E10

**BATTERY ELECTRIC VEHICLE**
- Electricity Mix 450

**FUEL CELL ELECTRIC VEHICLE**
- Hydrogen Mix
NUMBER OF FCEVS IN SELECTED MARKETS

Global number of vehicles
approx. 1 bln today
approx. 2 bln 2050

Data: IEA 2015b

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NEW REGISTRATIONS OF FCEVS IN SELECTED MARKETS

10 mln vehicles

2025 2030 2035 2040 2045 2050

Japan
EU 4
USA

Data: IEA 2015b
ANNUAL H₂ DEMAND OF FCEVS (IN 2DS HIGH H₂ SCENARIO)

Global hydrogen production today
45 – 50 mln t

7 mln t H₂ p.a.
WELL-TO-WHEEL GHG SAVINGS OF FCEVS COMPARED TO PETROL VEHICLES

Equates to approx. 8% of total mobility related emissions of the three markets compared to baseline (New Policy Scenario IEA 2014).
POLICY ASKS FOR THE HYDROGEN ECONOMY

- Production processes: cost, efficiency, flexibility
- Fuel cells: cost, efficiency, stability
- Long-term mass storage, R&D in materials-based storage
- Support launch of BUP/Micro CHP systems + FC vehicles
- Build-up of hydrogen supply and distribution infrastructure
- “Level playing field” + sector coupling
- Create/ensure consumer acceptance
Questions and Answers

www.shell.de/h2studie
www.shell.de/wasserstoffstudie
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